

## ON THE POLARIMETRIC SIGNATURE OF EMERGING MAGNETIC LOOPS IN THE QUIET-SUN

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## ABSTRACT

The abundance of Stokes  $V$  profiles dominated by one lobe at the locations of emergence of  $\Omega$ -shaped magnetic loops is evaluated. The emergence events were found in *Hinode* SOT/SP time-sequences of quiet-Sun regions. Such a study has the aim of confirming a prediction based on the basic geometrical and physical properties of emerging magnetic loops: Stokes  $V$  profiles dominated by one lobe are possibly the main polarimetric signature of these structures. In agreement with this prediction, 47% of the Stokes  $V$  profiles analyzed has an amplitude asymmetry  $|\delta a| > 0.3$ , while in the quiet-Sun the abundance is of about 30%. This excess with respect to the quiet-Sun is found consistently for whatever value of the threshold on the amplitude asymmetry. Such a result proves the goodness of the physical scenarios so far proposed for the interpretation of loop emergence events and may prompt the use of Stokes  $V$  profiles dominated by one lobe as a new proxy for their identification in observations with a good spectral sampling.

*Subject headings:* Sun: surface magnetism — Sun: photosphere — Sun: magnetic topology — Techniques: polarimetric

## 1. INTRODUCTION

The spectro-polarimeter SOT/SP (Lites et al. 2001) aboard the JAXA mission Solar-B (*Hinode*, Kosugi et al. 2007) allows one to perform high spatial resolution (0.3 arcsec), and high polarimetric sensitivity ( $10^{-3}$  the quiet-Sun continuum intensity) spectro-polarimetric observations of the solar photosphere in the Fe I 630 nm lines. Since its launch in 2006, SOT/SP provides to the solar community the conditions to achieve a breakthrough in the investigation of the quiet-Sun magnetism.

Recently, great attention has been dedicated by the solar community to the study of magnetic field emergence events in SOT/SP data. These were firstly pointed out either as small scale magnetic loops (loop cases; Centeno et al. 2007), or magnetized emerging granules with a single magnetic polarity (unipolar cases; Orozco Suárez et al. 2008). Latterly, in Martínez González & Bellot Rubio (2009), an extensive analysis of approximately 50 emerging loops anchored to the solar photosphere ( $\Omega$  loops) was presented. In Martínez González et al. (2010) both the topology and the dynamics of an emerging  $\Omega$  loop were derived. A similar study was presented in Ishikawa et al. (2010). More studies of magnetic field emergence events can be found in the literature: the ones of Martínez González et al. (2007), and Gömöry et al. (2010) performed on data from TIP (Collados et al. 1999), and the ones of Guglielmino et al. (2011), and Palacios et al. (2011) performed on data from IMaX (Martínez Pillet et al. 2011). A complete understanding of the emergence of magnetic fields in the quiet-Sun could considerably improve our knowledge of the solar photosphere (see the references in the introduction of Martínez González & Bellot Rubio 2009).

In spite of the rich literature on the emergence of mag-

netic fields in the solar photosphere, there is still a lack of knowledge about the typical polarimetric signatures associated to these events. In this work, the first analysis of the shapes of Stokes  $V$  profiles measured at the locations of  $\Omega$  loop emergence events in SOT/SP data is presented. The main goal of this study is to confirm the following prediction that can be outlined by considering the basic geometrical and physical properties of emerging  $\Omega$  loops: Stokes  $V$  profiles dominated by one lobe are possibly the main polarimetric signature associated to such events in the quiet-Sun.

The paper is organized as follows: the polarimetric signatures which are expected to be observed at the locations of an emerging  $\Omega$  loop are described in Sect. 2; the dataset and the analysis method adopted are presented in Sect. 3; the results of the analysis confirming the prediction made in Sect. 2 are presented and discussed in Sect. 4; the conclusions are outlined in Sect. 5.

2. POLARIMETRIC SIGNATURES OF AN EMERGING  $\Omega$  LOOP

Figure 1 shows a cartoon drawing of a  $\Omega$  loop which is emerging in a field-free environment at the disk center. More precisely, Fig. 1 represents the two phases which allow one to identify a loop emergence event in time-sequences of polarimetric data. In this figure, the different layers of the solar photosphere are marked with average values of the optical depth at 500 nm ( $\tau_{500}$ ). In the initial phase (**a** panel in Fig. 1) the top of the loop, dominated by transversal magnetic fields with respect to the line-of-sight (LOS) of an observer (e.g. **Obs1**), enters the photosphere producing a linear polarization signature (usually on top of granules, e.g. Ishikawa et al. 2010). In the following phase (**b** panel in Fig. 1), the loop emerges above the photosphere and two circular polarization signatures with opposite polarities, produced by the longitudinal fields with respect to the LOS, are observed (e.g. by the observer **Obs2**). The polarization signatures associated to these two phases of a magnetic loop emergence event are commonly used as proxies to identify emerging

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loops in polarimetric observations of the quiet-Sun (see the references in Sect. 1).

However, an in-depth understanding of  $\Omega$  loop emergence events requires dealing with the details of polarization measurements. In Ishikawa et al. (2010, Fig. 8) the authors derived the physical properties of an emerging  $\Omega$  loop by collecting one-dimensional (1D) slices retrieved from inversions of polarization measurements. It is worth pointing out that the authors had to deal with Stokes  $V$  profiles with strong asymmetries: two Stokes  $V$  profiles dominated by one lobe were observed in two of the pixels of the loop (see Fig. 3 of Ishikawa et al. 2010). In the following it is shown that it is possible to predict that this kind of profiles are possibly the main polarimetric signature associated to emerging  $\Omega$  loops.

The LOS **Obs2**, crossing one of the loop's foot-points in Fig. 1, passes first through a field-free layer which fills the region  $\tau_{500} = 0.01 - 0.1$ , and then through a magnetized layer which fills the region  $\tau_{500} = 0.1 - 1$ . If the location of the foot-point crossed by **Obs2** is an up-flow (as usual in emergence events), the plasma velocity along the LOS in the region  $\tau_{500} = 0.1 - 1$  is negative and of the order of several kilometers per second, while the same quantity in the region  $\tau_{500} = 0.01 - 0.1$  is expected to be considerably smaller in absolute value (see e.g. Viticchié & Vitas 2011). From the extensive literature on the formation of strongly asymmetric Stokes  $V$  profiles in Visible spectral lines from 1D stratifications one can conclude that an atmospheric configuration like the one described above can give rise to a Stokes  $V$  profile dominated by the blue lobe under very different conditions: for either sharp or smooth transitions between the magnetized region and the field-free one, for either strong or weak magnetic field regimes, for either vertical or inclined magnetic fields with respect to the LOS. Conversely, if the foot-point is located in a down-flow, a profile dominated by the red lobe is very likely to be formed (Viticchié & Vitas 2011; Sainz Dalda et al. 2011). Similar arguments can be used to predict that the atmospheric properties along the LOS **Obs3** can give rise to Stokes  $V$  profiles dominated by one lobe as well (Grossmann-Doerth et al. 2000; Viticchié & Vitas 2011; Sainz Dalda et al. 2011). Figure 3 of Ishikawa et al. (2010) offers one a fast verification of the prediction outlined above. In Sect. 4, much stronger arguments in favour of the connection between  $\Omega$  loop emergence events and the observation of Stokes  $V$  profiles dominated by one lobe are presented.

The polarimetric signatures produced by the emerging  $\Omega$  loop in Fig. 1 are assumed to have dimensions larger than the resolution element of modern spectro-polarimetric observations, i.e. the loop structure is resolved<sup>2</sup>. This assumption does not imply that the magnetic fields of the loop are completely resolved, it rather implies that a dominant  $\Omega$ -shaped magnetic structure can be pointed out from the data. This structure is the one which is considered to be dominant in each pixel of the observed loops. For this reason one can use the properties of 1D stratifications to predict the asymmetries of Stokes  $V$  profiles at the locations of emerging magnetic loops.

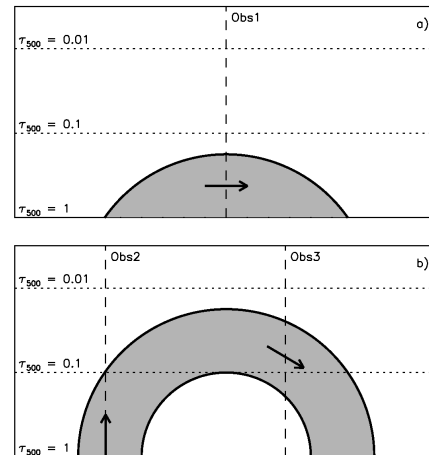


FIG. 1.— Cartoon drawing of a magnetic  $\Omega$  loop (shaded area) emerging above the solar photosphere. Upper panel: initial phase producing the linear polarization signature. Lower panel: the following phase, with the loop standing above the photosphere, producing the two circular polarization signatures. The location of the photospheric layer is marked by the average  $\tau_{500} = 1$  level. The upper photosphere layers are marked by the average  $\tau_{500} = 0.1$ , and  $0.01$  levels (horizontal dotted lines). The dashed vertical lines show three LOS examples crossing the loop structure at different instants and locations. The arrows crossing the LOS represent the direction of the magnetic field vector.

### 3. DATASET AND ANALYSIS METHOD

In order to have a large statistics of Stokes  $V$  profiles from the locations of emerging magnetic loops one can use the time-sequences analyzed in Martínez González & Bellot Rubio (2009). This is so far the study with the richest record of emergence events of  $\Omega$  loops in the quiet-Sun. In detail, all the time-sequences reported in Table 1 of Martínez González & Bellot Rubio (2009), with exception made for the sequence of September 26th (due to problems in downloading the dataset from the *Hinode* archive), were analyzed. One can refer to both Table 1 and the second paragraph of Sect. 2 of Martínez González & Bellot Rubio (2009) for the description of the datasets.

As reported in Sect. 2, a magnetic  $\Omega$  loop can be identified in polarimetric data as “a linear polarization signature flanked by circular polarization signatures with opposite polarities” (e.g. Martínez González & Bellot Rubio 2009). In the analysis here presented, those events in which the linear and circular polarization signatures had, at least for one wavelength,  $\max(|Q|, |U|) > 8 \times 10^{-3}$  and  $\max(|V|) > 6 \times 10^{-3}$  in each pixel, respectively, were considered. Besides this, a minimum area of four pixels for each polarization signature was required<sup>3</sup>. Each emergence event was taken out of the time-sequences by picking out a subsequence of sub-fields (of  $\simeq 2.7 \times 2.7$  arcsec<sup>2</sup>) around the location where the emergence was found to take place. Spurious polarimetric signals due to magnetic fields in the selected sub-fields were then carefully removed along

<sup>2</sup> For a discussion on the polarimetric signature produced by unresolved magnetic loops refer to Steiner (2000).

<sup>3</sup> Strong and well-resolved polarization signatures with a maximum Stokes  $V$  amplitude above three times the polarimetric sensitivity of the observations, i.e.  $1.7 \times 10^{-3}$  in units of the average continuum intensity (see Martínez González & Bellot Rubio 2009), were considered. The higher threshold for the individuation of the linear polarization signature allows one to point out sound cases.

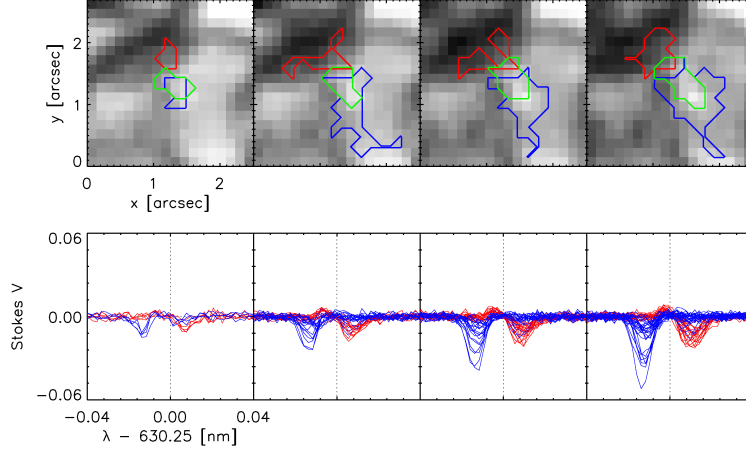


FIG. 2.— An example of a  $\Omega$  loop emergence event extracted from the analyzed time-sequences. Upper row: sub-sequence of Stokes  $I$  continuum sub-fields centered around the location of the emergence event. The contours mark the positions of the positive circular polarization signature (red contours), the negative circular polarization signature (blue contours), and the linear polarization signature (green contours). These allow one to point out the emergence event according to the criteria used in Martínez González & Bellot Rubio (2009). The contour regions have areas larger than four pixels of *Hinode* SOT/SP and  $\max(|Q|, |U|) > 8 \times 10^{-3}$  and  $\max(|V|) > 6 \times 10^{-3}$  (see Sect. 3). Lower row: Stokes  $V$  profiles with  $|\delta a| > 0.3$  from the pixels in the locations of the two circular polarization signatures marked by the blue and red contours in the upper row. The colors encode the polarimetric signature from which the profiles were picked.

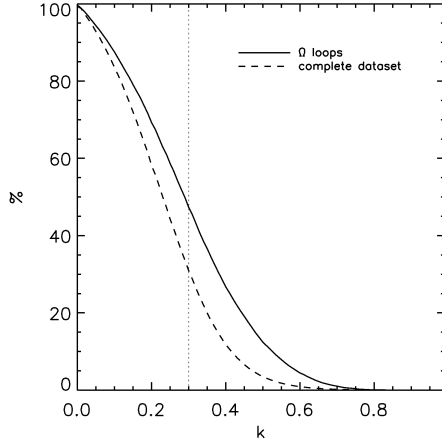


FIG. 3.— Abundances of Stokes  $V$  profiles with  $|\delta a| > k$  as functions of  $k$ . The solid line shows the abundances derived at the locations of emergence of magnetic loops; the dashed line shows the ones derived from the complete quiet-Sun dataset of all the time-sequences when considering the profiles with  $\max(|V|) > 0.006$  (consistent with Sect. 3). The dotted vertical line marks the threshold value here used to evaluate the abundances, i.e.  $k = 0.3$ .

the whole sub-sequence by visual inspection.

An example of emergence event extracted from the analyzed sequences is shown in the upper row of Fig. 2 in which both the linear and the circular polarization signatures that allow one to point out the  $\Omega$  loop were marked (contours). A total of 40 events were found in the analyzed sequences; these presented a large variety of properties which were investigated in detail in Martínez González & Bellot Rubio (2009). Here the abundance of Stokes  $V$  profiles dominated by one lobe at the locations of the circular polarization signatures of the loops was studied.

The lower row of Fig. 2 shows a fraction of the Stokes  $V$  profiles at the locations of the circular polarization signatures of the emergence event in the upper row. In detail, among the Stokes  $V$  profiles observed at the locations of the circular polarization signatures of the  $\Omega$  loop, the

ones with  $|\delta a| = \left| \frac{a_b}{a_b + |a_r|} - \frac{|a_r|}{a_b + |a_r|} \right| > 0.3$  were represented<sup>4</sup>.  $\delta a$  is the amplitude asymmetry of a Stokes  $V$ : the higher the  $|\delta a|$  the more the Stokes  $V$  is dominated by one lobe.

One can understand the formation the Stokes  $V$  profiles in Fig. 2 by referring to Sect. 2 and Fig. 2 (Obs2). The signature with the positive polarity, mostly located in a down-flow, is characterized by Stokes  $V$  profiles dominated by the red lobe. The negative one, located on a bright granule, is characterized by profiles dominated by the blue lobe. The observations of these polarimetric signatures were predicted in Sect. 2.

By exploiting all the 40  $\Omega$  loop emergence events individuated in the analyzed time-sequences one can analyze more profiles and, eventually, evaluate the abundance of Stokes  $V$  profiles dominated by one lobe at the locations of such events. To do this, all the Stokes  $V$  profiles from the circular polarization signatures which allow one to identify the emergence events were collected; these were 12256 profiles. Those profiles with  $|\delta a| > 0.3$  were the ones considered to be dominated by one lobe (see e.g. Fig. 2).

#### 4. RESULTS AND DISCUSSION

The Stokes  $V$  profiles with  $|\delta a| > 0.3$  make up 5799 of the 12256 of the whole archive (i.e. 47%). This means that nearly one in every two Stokes  $V$  profiles observed at the locations of emerging magnetic loops is dominated either by the blue lobe or by the red lobe. Such a result confirms the prediction made in Sect. 2, and allows one to put forward Stokes  $V$  profiles dominated by one lobe as a new proxy for emerging  $\Omega$  loops in polarimetric observations with good spectral sampling. Even though the abundance here derived stemmed from an arbitrary threshold on the amplitude asymmetry of the analyzed circular polarization signals, the plentitude of Stokes  $V$  profiles dominated by one lobe at the locations of emerging magnetic loops can be proved in an alternative way. Figure 3 shows the abundances for different values of the threshold ( $k$  in Fig. 3) on the amplitude asymmetry

<sup>4</sup> In the formula,  $a_b$  ( $a_r$ ) is the amplitude of the blue (red) lobe.

in both the sample described at the end of Sect. 3 and the complete quiet-Sun dataset of all the time-sequences. On the one hand, the result reveals that the abundance strongly depends on the threshold value. On the other hand, it shows that there is a considerable excess of profiles with large  $|\delta a|$  at the locations of loop emergence events with respect to the quiet-Sun. This result does not depend on the value of the threshold, and further supports the prediction made in Sect.2.

Polarimetric observations of loop emergence events performed with other instruments do not present the same abundance of extremely asymmetric profiles. Gömöry et al. (2010) presented a study of the shapes of Stokes  $V$  profiles observed in the two infra-red (IR) Fe I lines at 1565 nm with TIP (Collados et al. 1999) at 1 arcsec spatial resolution. The profiles they showed in Fig. 2 are anti-symmetric profiles. Such a lack of asymmetry can be understood by referring to Grossmann-Doerth et al. (1989) in which the authors explained the different conditions which produce strong asymmetries in Stokes  $V$  profiles in the Visible and in the IR. In Guglielmino et al. (2011) the authors pointed out the observation of asymmetric profiles in one emergence event observed with IMAx (Martínez Pillet et al. 2011) in the Fe I 520 nm line. A detailed analysis of the profiles observed by IMAx at the locations of emergence events would be important to complement the study presented here.

Finally, the results shown here allow one to complement the knowledge about the origin of Stokes  $V$  profiles dominated by one lobe observed by SOT/SP in the quiet-Sun. In detail, in Viticchié & Vitas (2011) the authors reported on the observation of such profiles at the borders of network patches in the dataset of Lites et al. (2008), while in Orozco Suárez et al. (2008) these were found at the locations of unipolar emergence events.

## 5. CONCLUSIONS

The first study of the shapes of Stokes  $V$  profiles observed at the locations of emerging magnetic  $\Omega$  loops found in SOT/SP time-sequences of the quiet-Sun is presented. It focuses on those loops which can be pointed out adopting the standard method based on the detection of both linear and circular polarization signatures in *Hinode* time-sequences of the quiet-Sun (see e.g. Martínez González & Bellot Rubio 2009). 47% of the profiles observed at the locations of such events have an

amplitude asymmetry  $|\delta a| > 0.3$ , i.e. are dominated by either the blue lobe or the red lobe. Such a value quantifies the excess of the profiles dominated by one lobe at the locations of magnetic loop emergence events with respect to their abundance in the complete quiet-Sun dataset of all the time-sequences.

This result confirms the prediction of the Stokes  $V$  profiles that are expected to be observed at the locations of emerging loops outlined in Sect. 2. The different LOS crossing the structure of a loop are expected to define 1D stratifications which are known to produce Stokes  $V$  profiles dominated by one lobe under very different conditions in Visible spectral lines (Grossmann-Doerth et al. 1989; Steiner 2000; Grossmann-Doerth et al. 2000; Viticchié & Vitas 2011; Sainz Dalda et al. 2011). The large abundance of these profiles at the locations of loop emergence events confirms the goodness of the physical scenarios so far proposed to interpret such events (e.g. Martínez González & Bellot Rubio 2009) and may prompt the use of Stokes  $V$  profiles dominated by one lobe as proxies to individuate emerging magnetic loops in spectropolarimetric observations with good spectral sampling.

The work presented here must be considered as a starting point for more refined studies of emergence events which, for example, might be aimed to: point out various emergence configurations, understand the temporal evolution of the Stokes  $V$  profiles as a loop emerges/evolves, measure the siphon-flows into the loops.

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